Characterization of SNS Low-Level RF System

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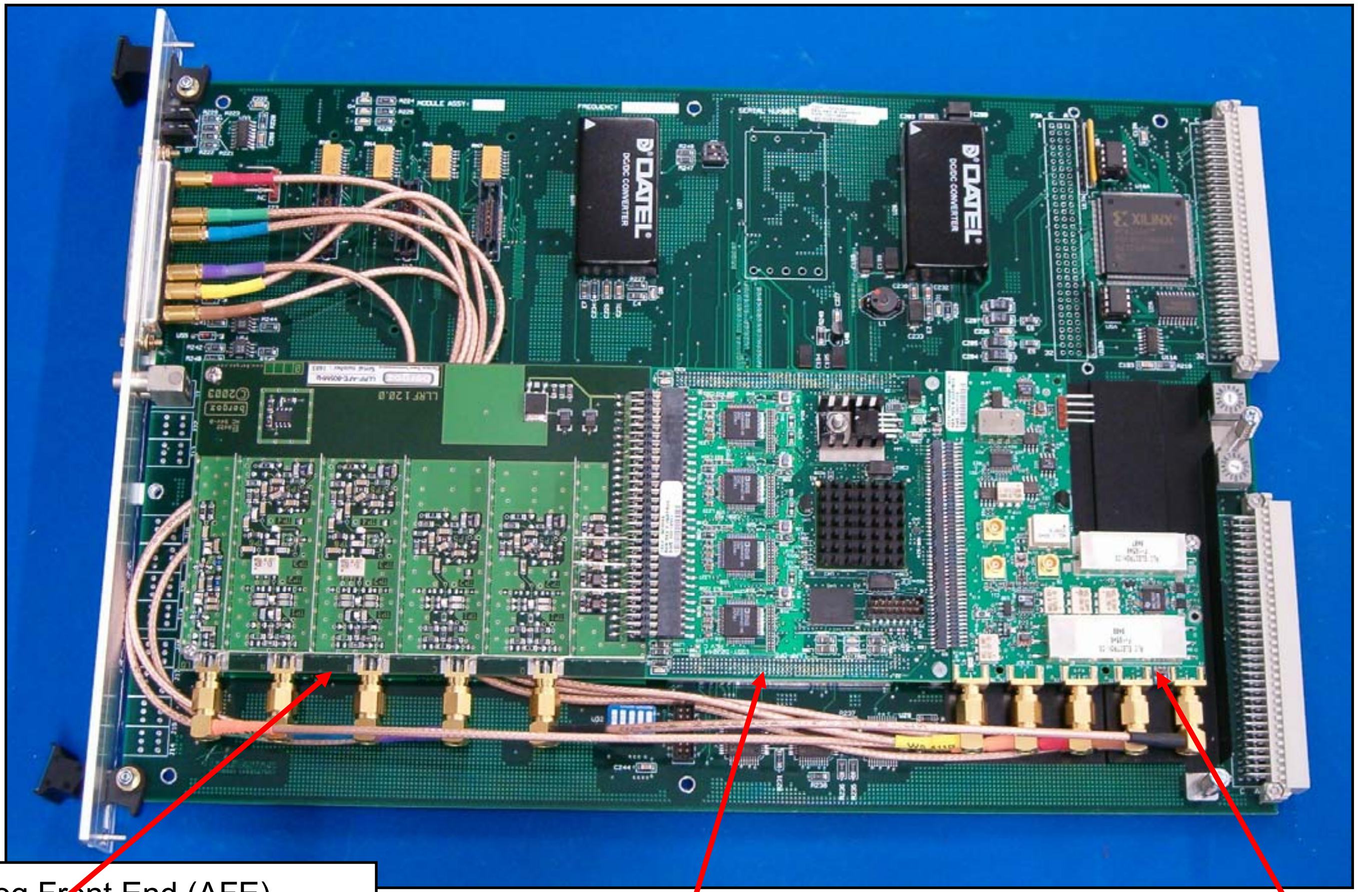
SNS LLRF System

- **System hardware overview**
  - implemented functionalities
  - development system
- **System characteristics**
  - noise levels
  - Loop gain/frequency & transient response
- **Operation automations**
  - cavity filling
  - adaptive feed forward compensations

SNS FCM = VXI + DFE + AFE + RFO

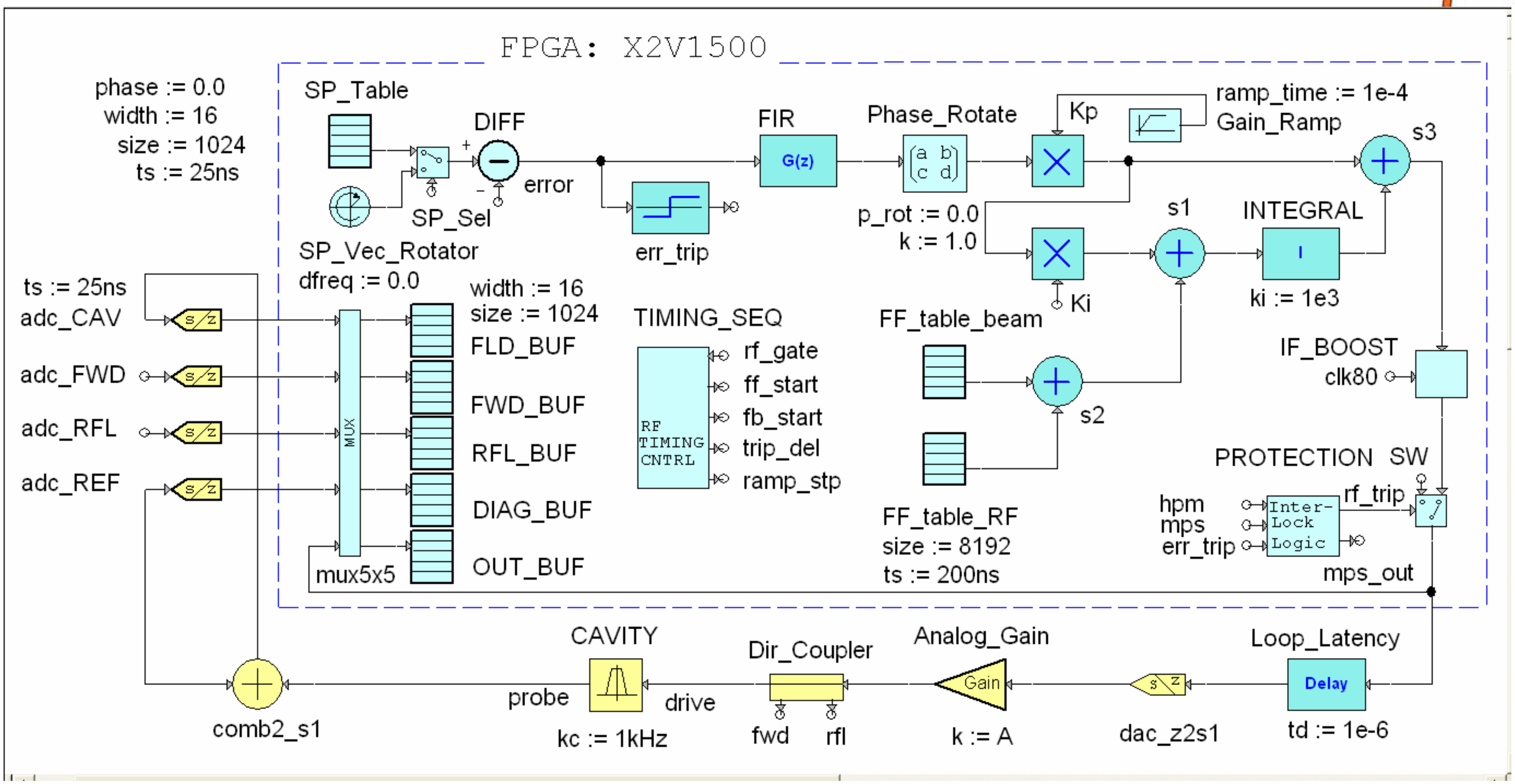


Analog Front End (AFE)
Down-converting channels:
Incident and Reflected RF
(402.5 or 805 MHz)
IF channels:
Cavity and Reference (50 MHz)

Digital Front End (DFE)
Four 14 bit, 40 MHz ADC channels
One Virtex II FPGA
(XC2V1500 – 1.5M gates)

RF Output (RFO)
Clock & PLL circuitry
One 14 bit, 80 MHz DAC
Up-Conversion to 402.5/805 MHz
Filtering

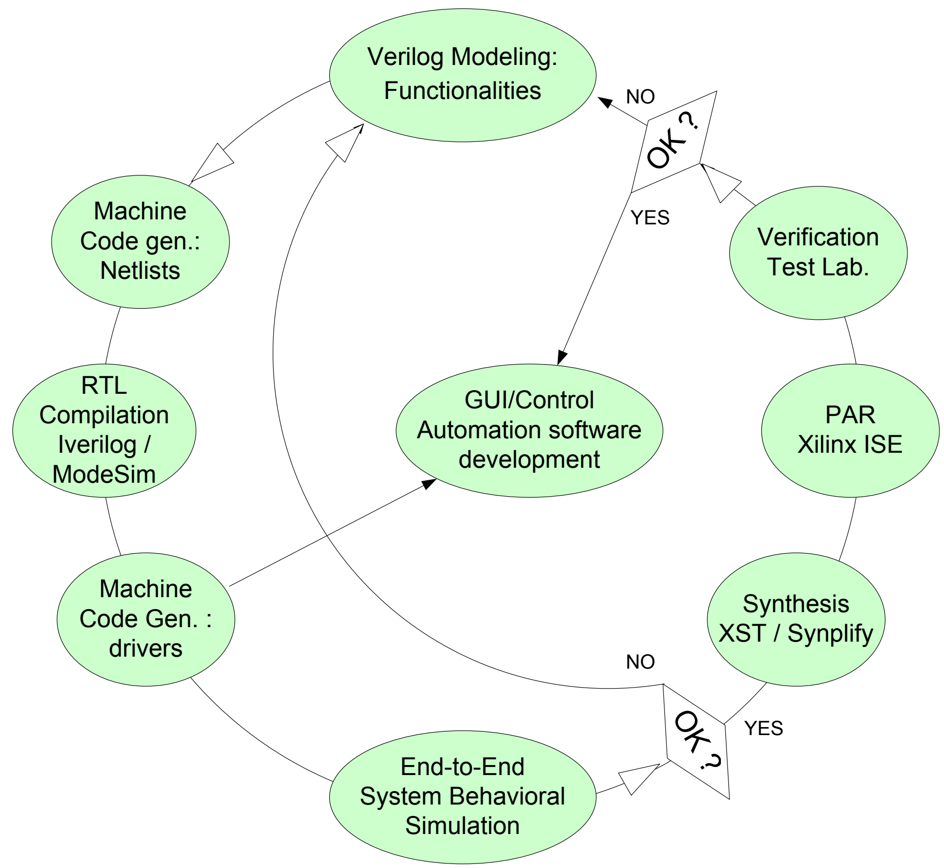
SNS LLRF : implemented controller hardware



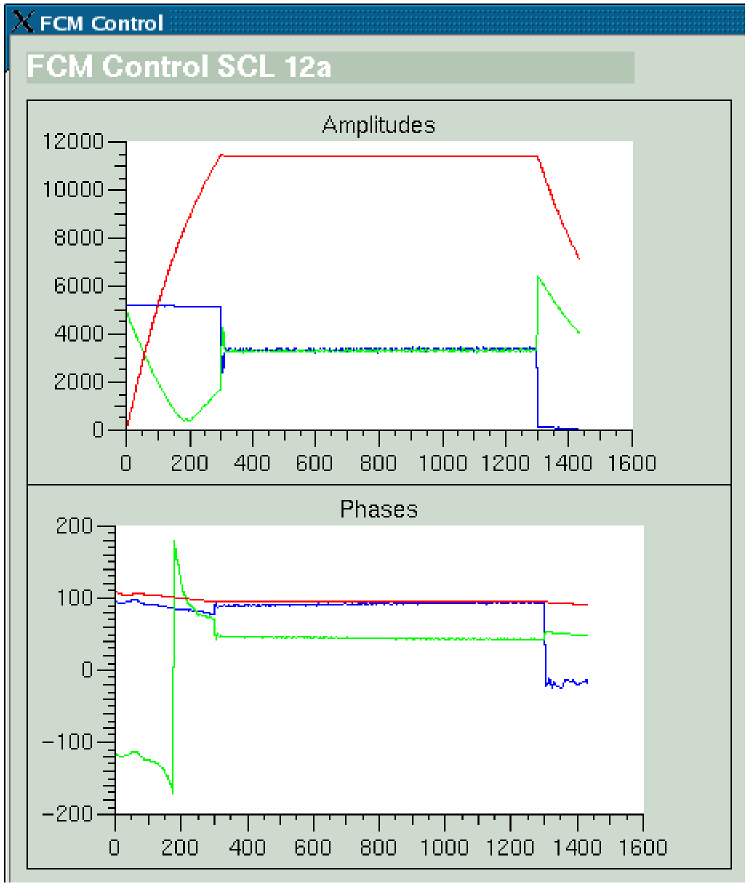
- Classic vector P-I control
- Dual switched FF tables
- SP table+Cordic phase rotator
- Digital IF output synthesis
- Five DSO signal trace buffers
- Protection interlocks, and etc.

SNS LLRF : hardware development system

- **Development Process**
  - Verilog modeling
  - Machine code/driver generation
  - Co-simulations
  - Synthesis/lab. verification.
- **Why need this system ?**
  - Reliable development and support.



FCM noise floor



Typical FCM signal data quality over a single RF pulse.

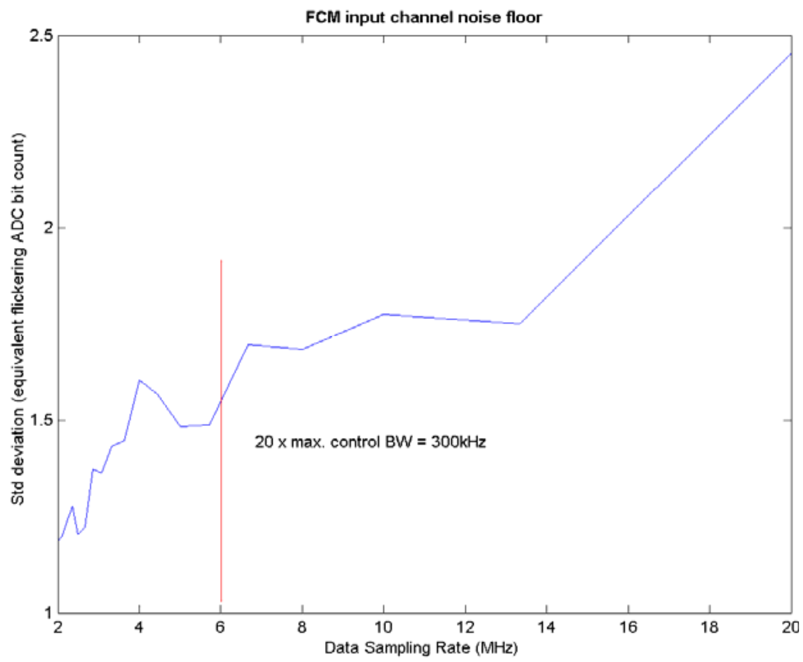
Noise sources:

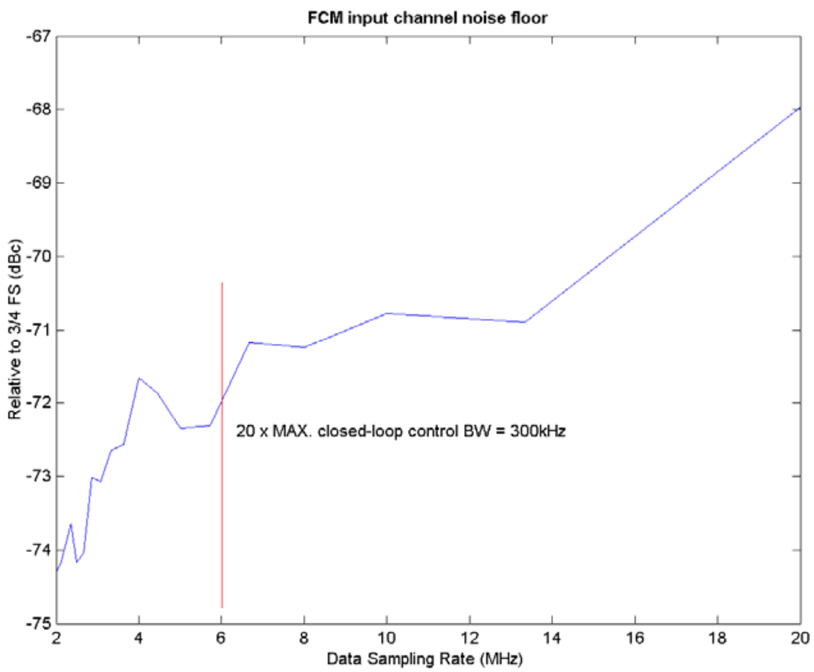
- **Data quantization,**
- **ADC/DAC clock jitter,**
- **Coupled digital noise**
- **Analog RF interferences**
- **Switching noise of PS**

FCM noise floor is well below the level required for

1%/ 1 deg.

FCM noise floor





Frequency response - analytical method

Simplistic Type I , 2nd + order controller w/delay

$$G(s) = A \cdot K_p \cdot K_c \cdot \frac{(s+K_i)}{s(s+K_c)} \cdot e^{-\tau s}$$ Routh-Hurwitz criterion -> $$A \cdot \mathbf{K_p} \cdot < \frac{4}{3 \cdot \tau \cdot K_c}$$

Constraints:

1. Total Loop delay (analog delay + digital latency)

- Adds more poles to the system - > instabilities.
- limits gain-bandwidth product $A \cdot K_p \cdot K_c$,
  - Given Kc, usable proportional gain AxKp is limited,
    - Thus limits the closed-loop control bandwidth,
      - In SC case, also affects the amount of FB control errors.

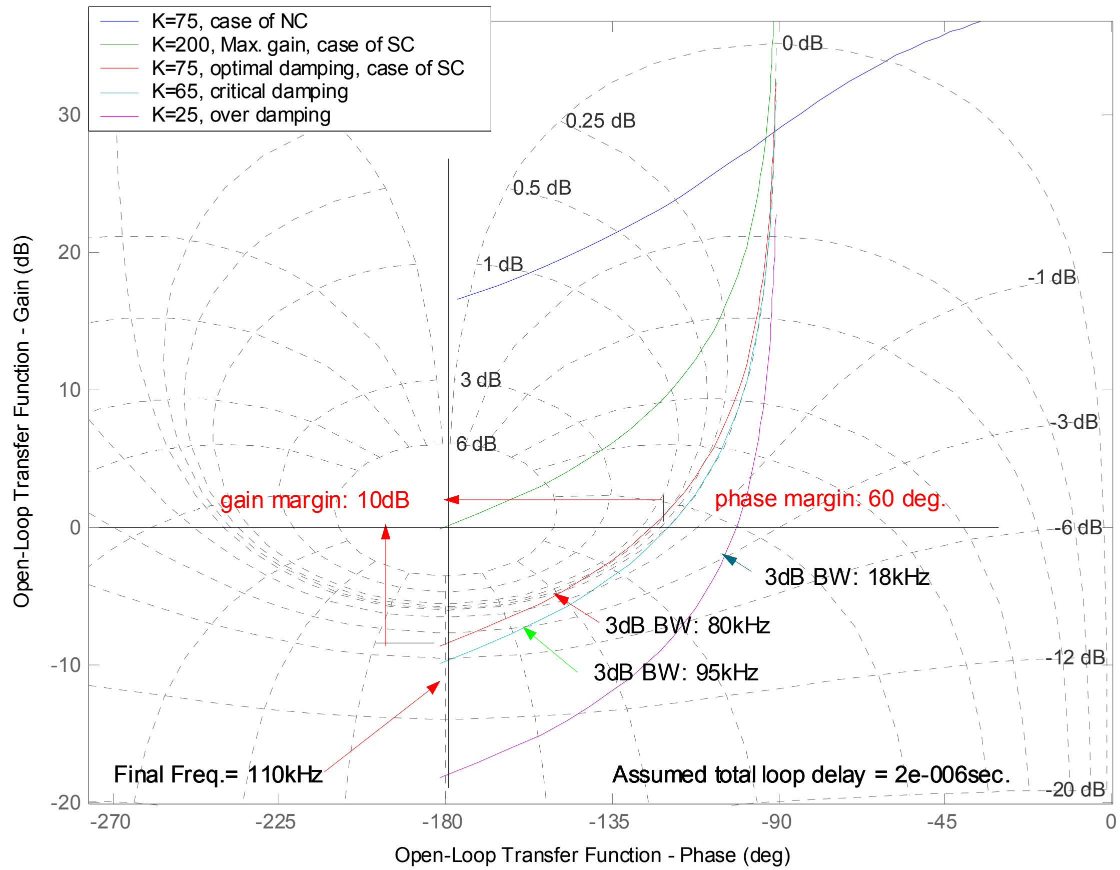
2. Quantization noise

SNS LLRF: System characteristics

Frequency response - graphic method

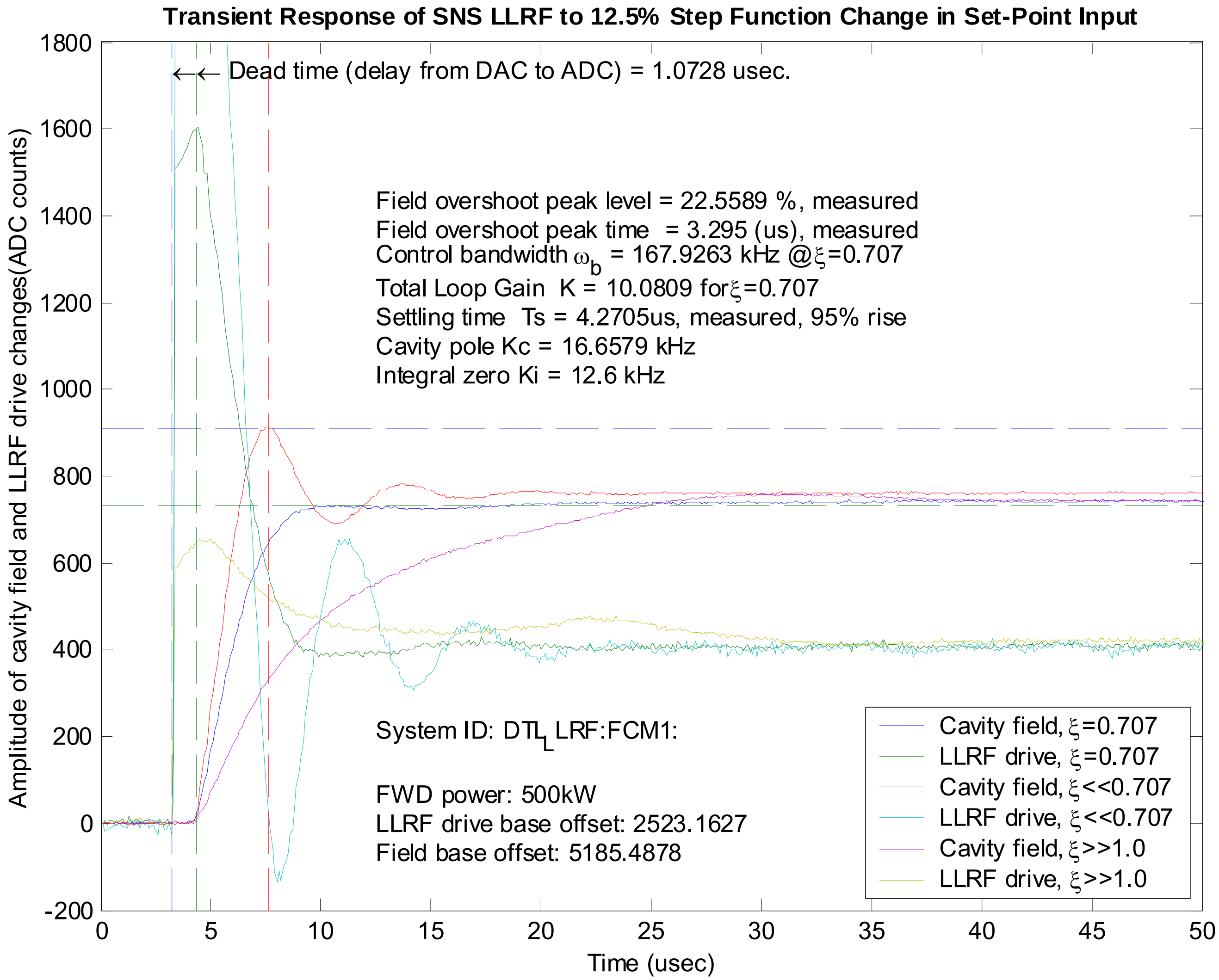
- assuming same system transfer function

Nichols Chart for SNS RF



SNS LLRF: System characteristics

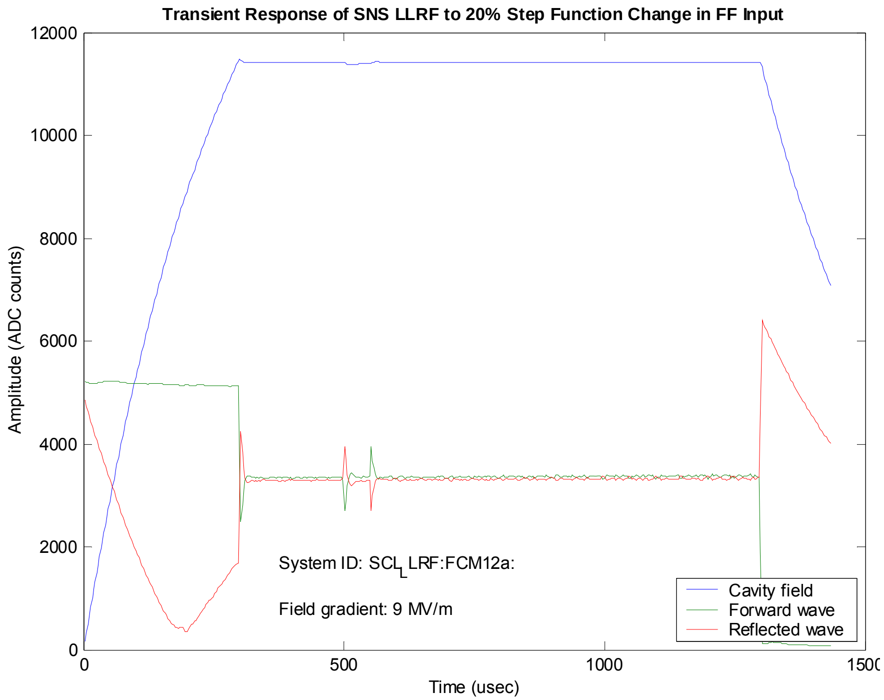
Transient response to step change – NC cavity

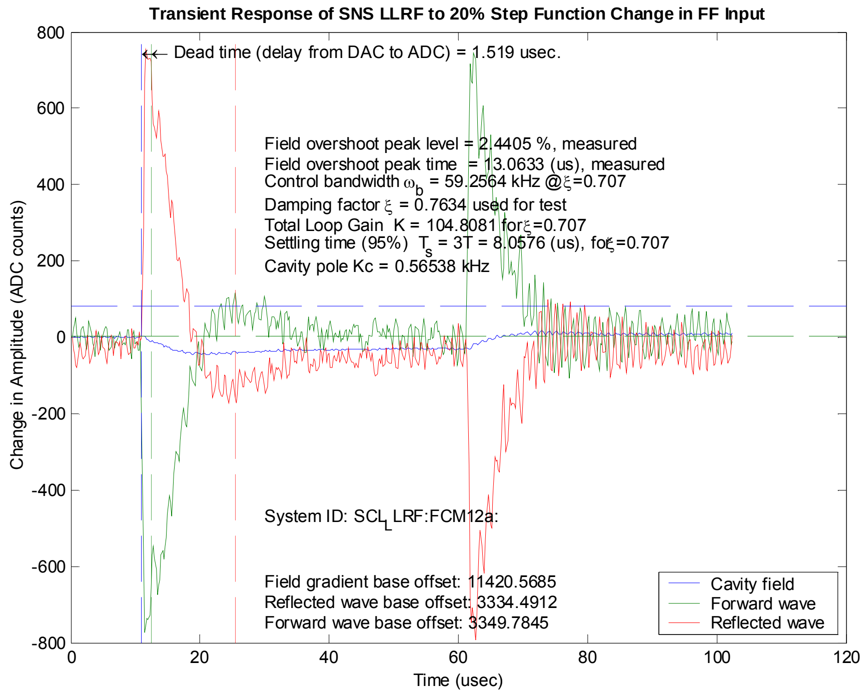


- 12.5% Step to SP input
- FWD PWR @ 500kW
- Cavity BW: 16.7kHz
- 3dB Cntrl BW: 167kHz
- Loop gain: 10

SNS LLRF : System characteristics

Transient response to test pulse - SC cavity



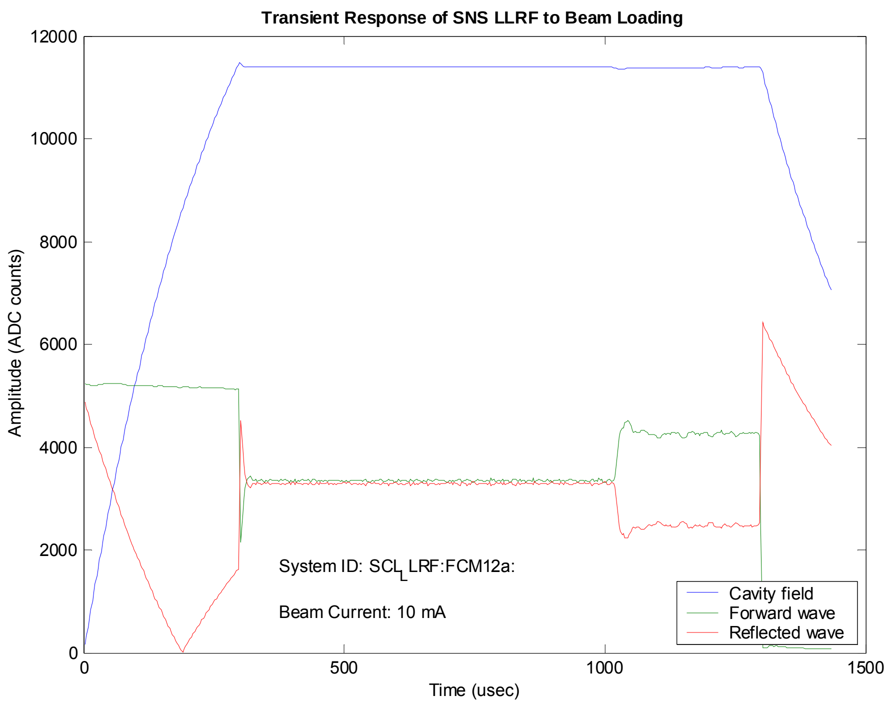


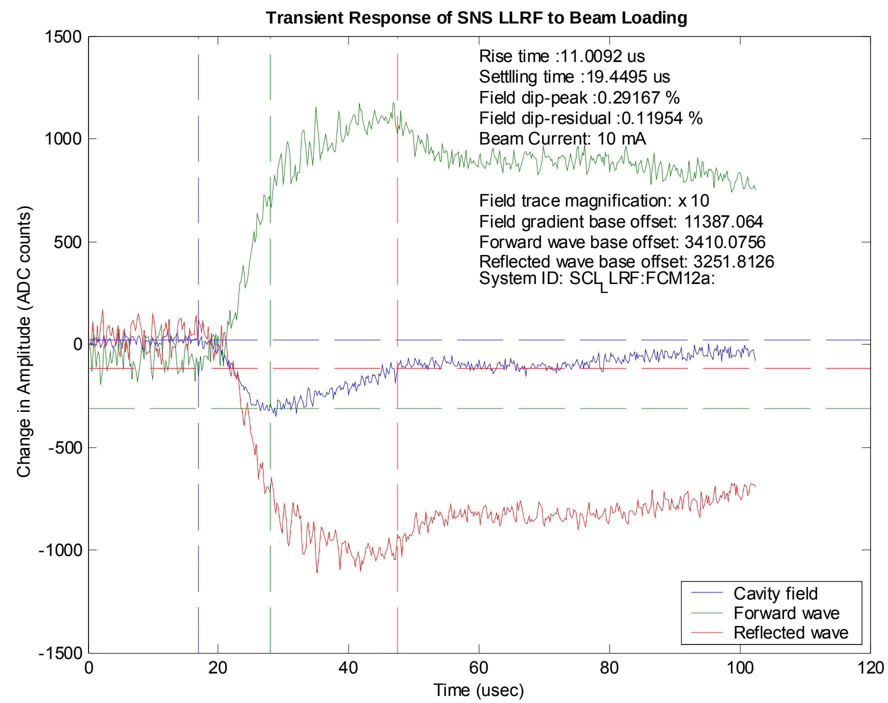
SCL-12a @ 9MV/m response to test rectangular pulse to FF input

- Closed-loop control bandwidth:≈59kHz for critically damped, cavity BW: 0.56kHz
- Total loop gain tested:≈ 89, 104 required for critical damping

SNS LLRF : System characteristics

Transient response to beam loading with no FF assistance





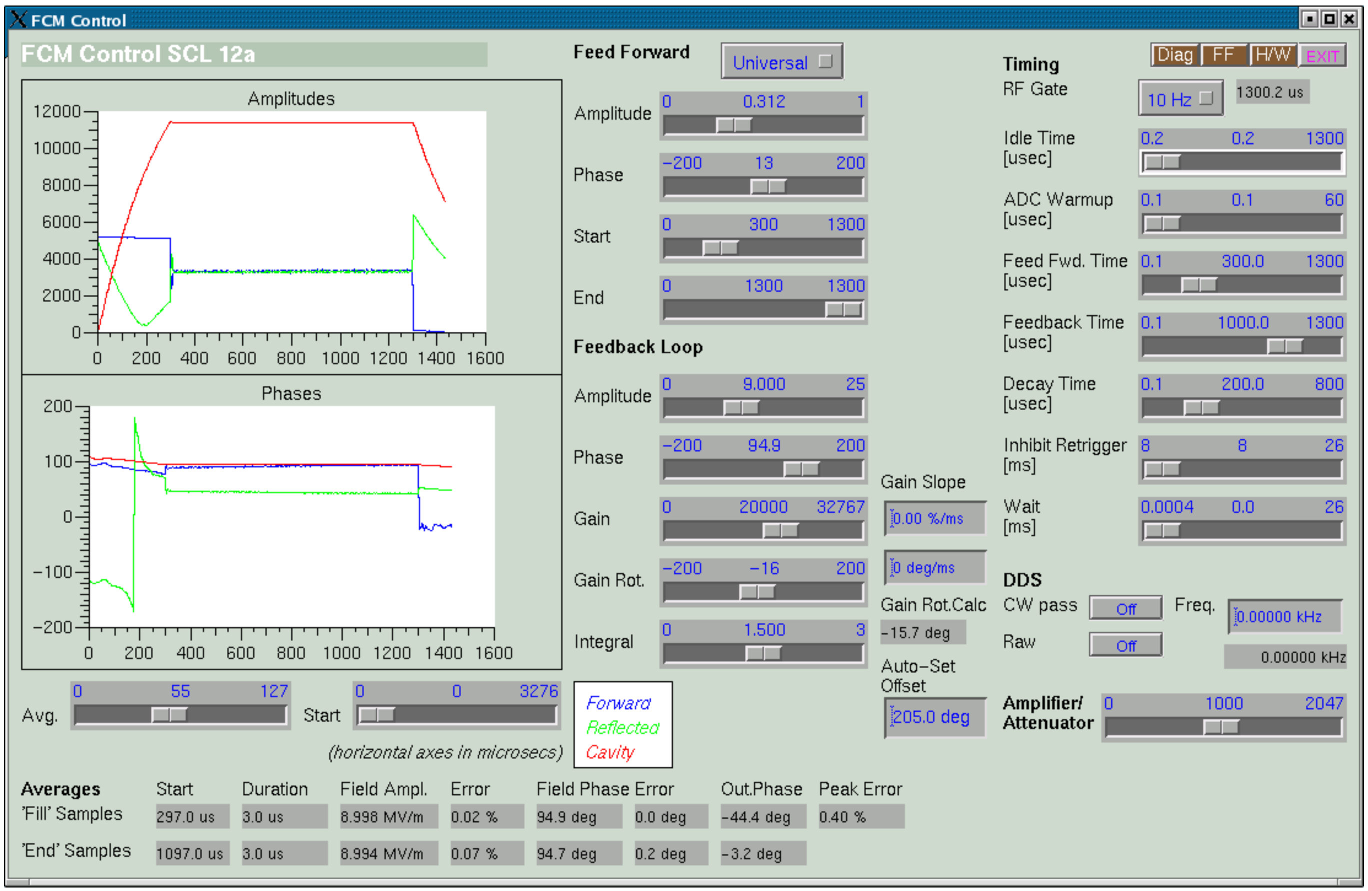
SCL-12a @ 9MV/m response to 10mA/300us beam pulse

- Beam rise time: ≈ 10us, feedback action delay time: ???
- Settling time of proportional feedback control: ≈19.5us
- Damping ratio: 0.76 ; Peak field error: 0.3% ; Residual error right after settling : 0.12%
- AFF for beam loading compensation ?

SNS LLRF : Operation methods

Cavity filling in in open-loop with FF first, and then feedback control during flattop.

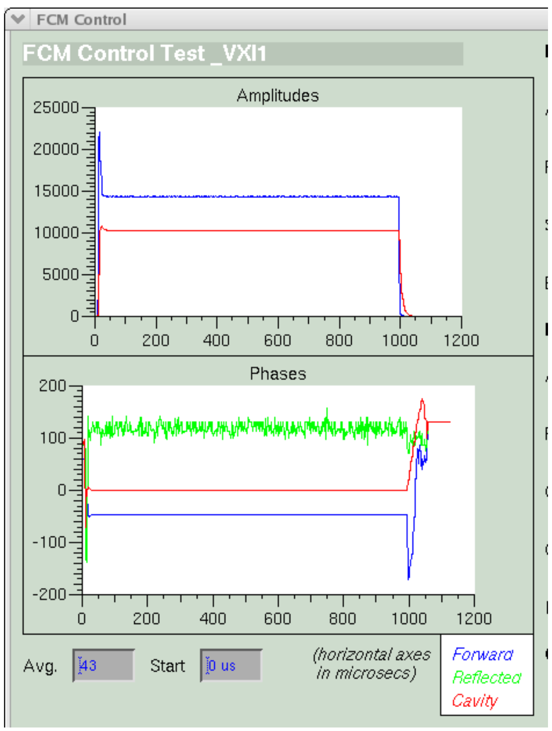
Automation software currently is being used on all 100 commissioned systems (both SC and NC).

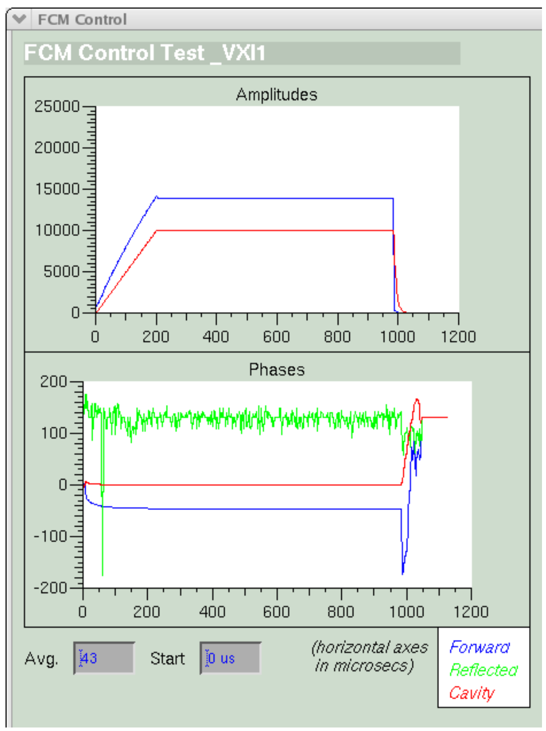


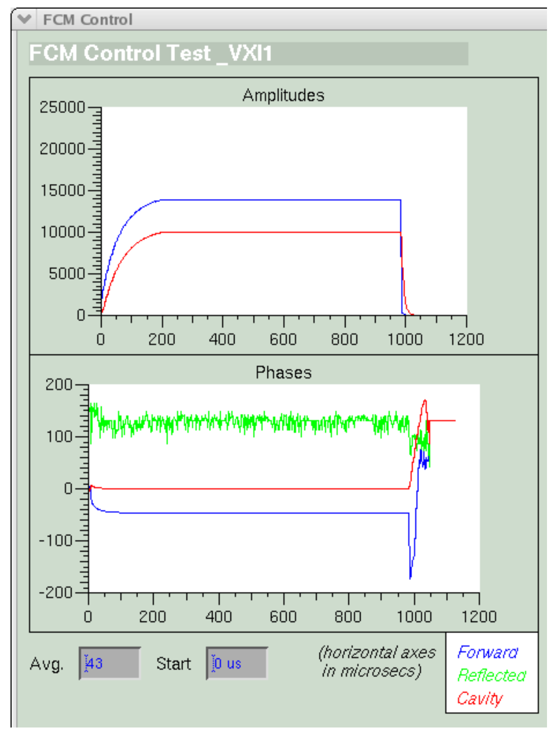
An option for NC cavities:

RF turn-on with FB control only, no FF for cavity filling, but uses a SP curve to modify RF drive overshoot.

Straight-up	**linear ramp**	**Exp. ramp**







SNS LLRF : Operation methods

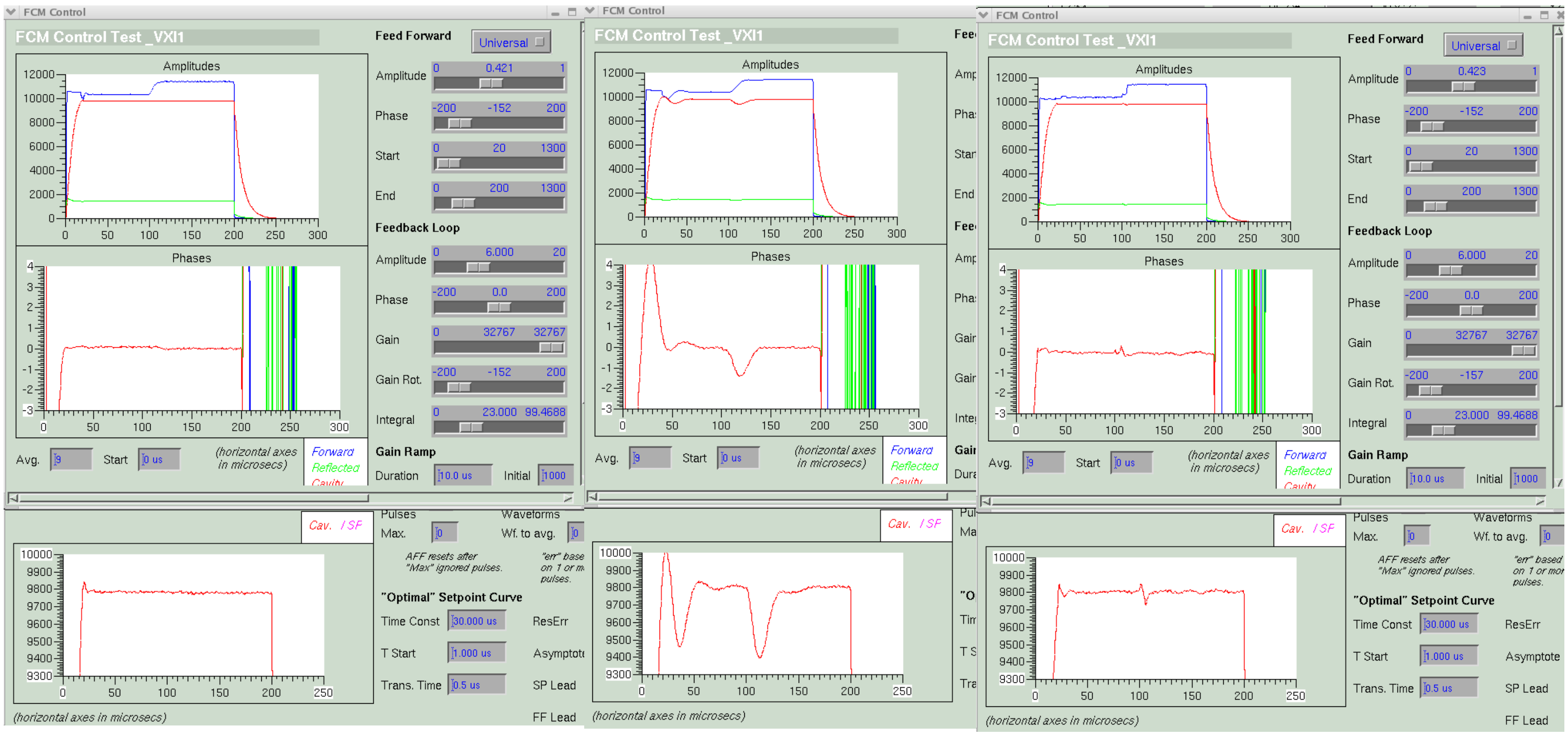
Two AFF compensation algorithms under test

(with 100 us simulated un-chopped beam, 15us rise time)

AFF ON — **IQ mod. (SNS)**

AFF OFF

AFF ON — **Vector mod. (Alexander)**

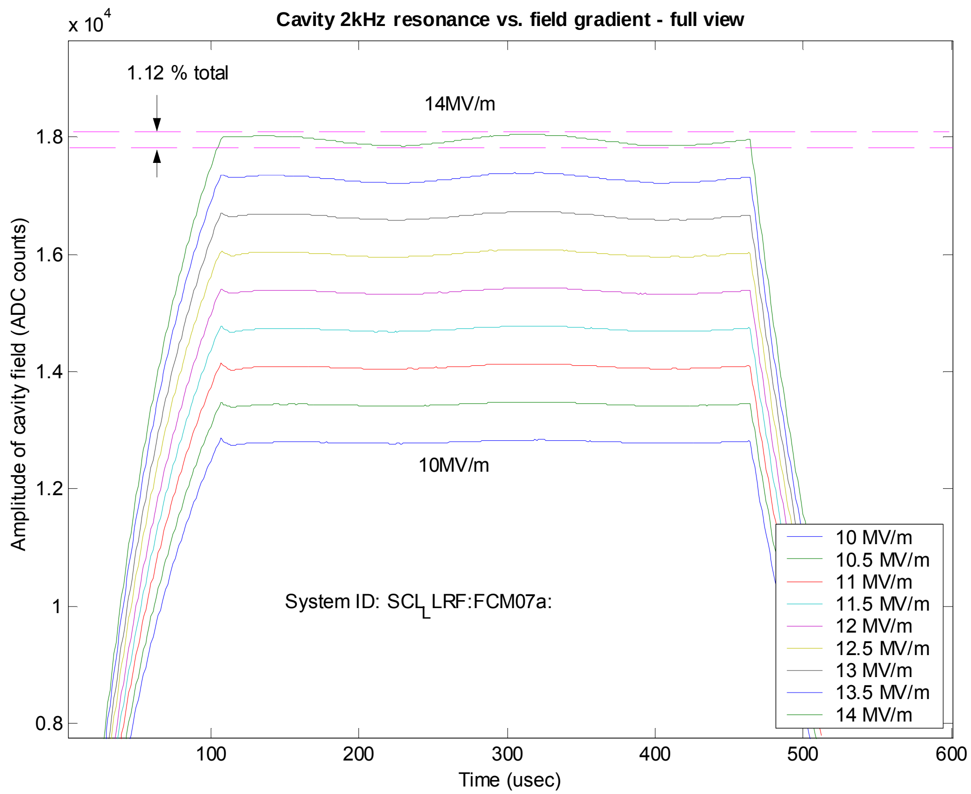


SNS LLRF : DSO buffer feature applications

Example 1:

Scanning field gradient setting to observe the “2kHz” mechanical mode of medium-beta cavities which becomes prominent when the cavity is run at a gradient much beyond the designed 10 MV/m

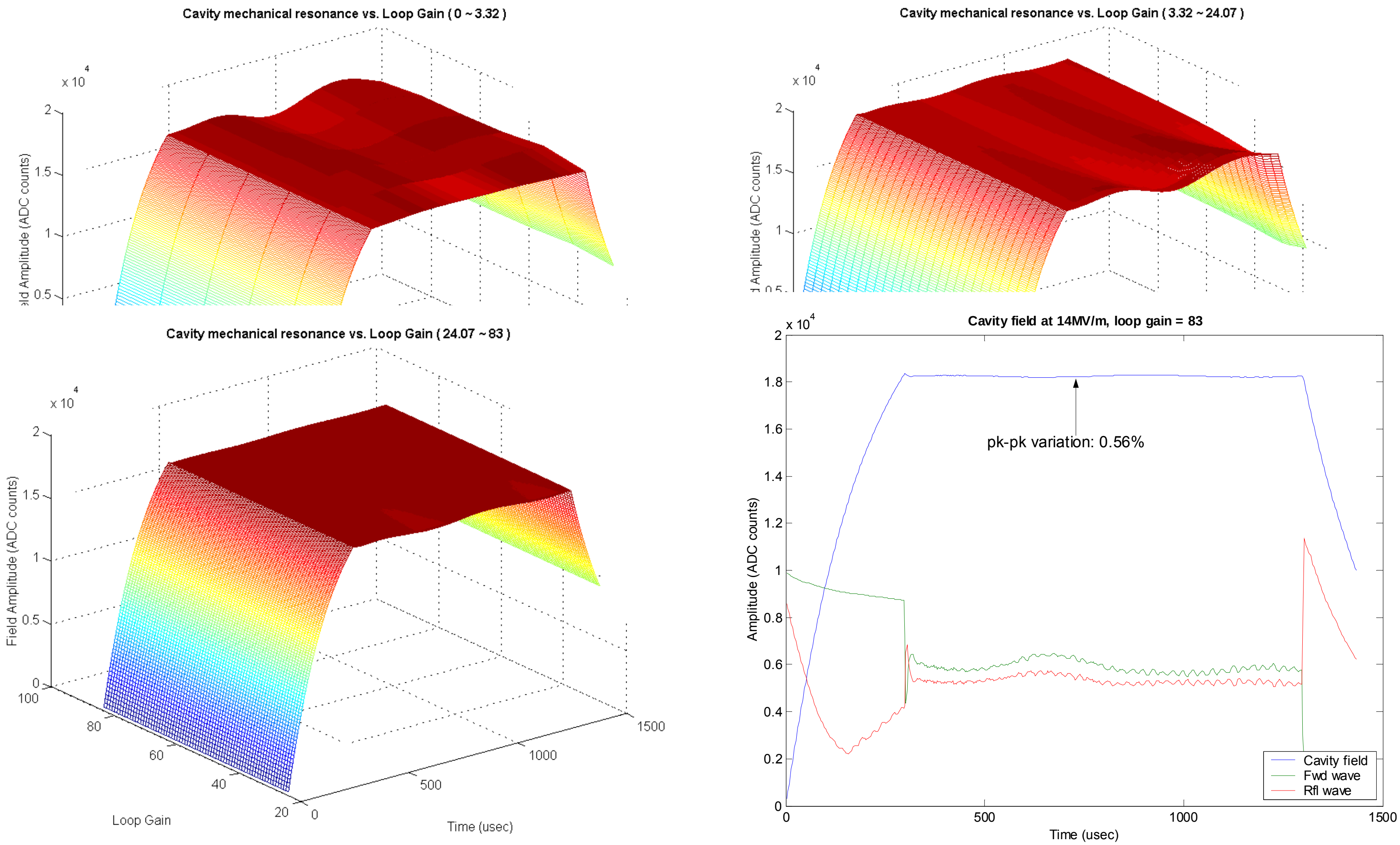
(note: half gain)



SNS LLRF : DSO buffer feature applications

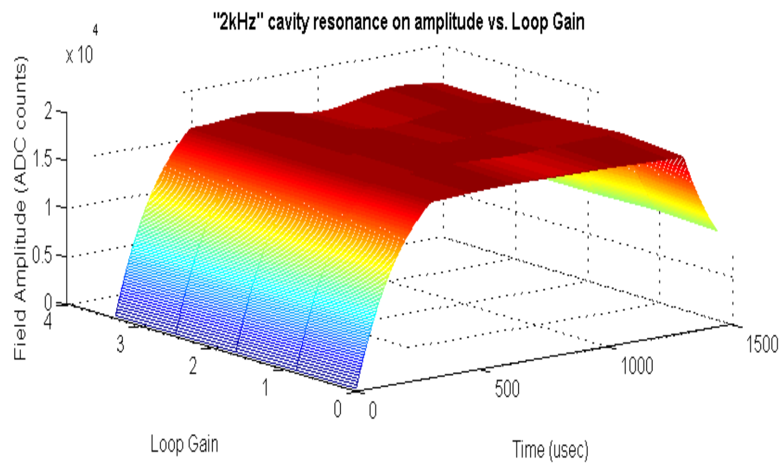
Example 2:

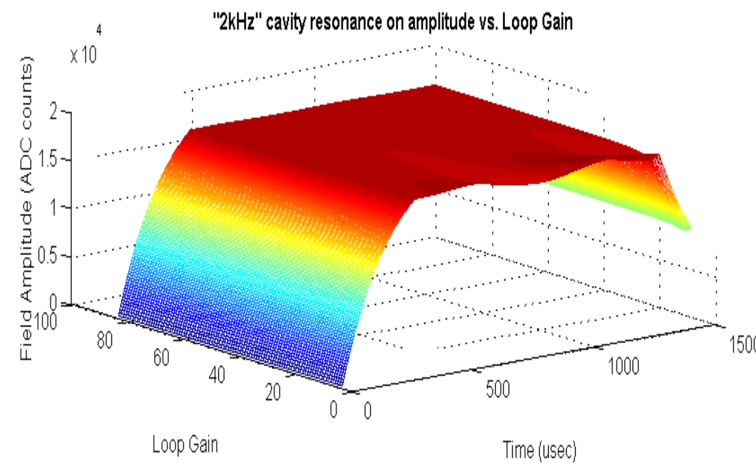
Scanning loop gain to see its effectiveness on controlling “2kHz” mode.

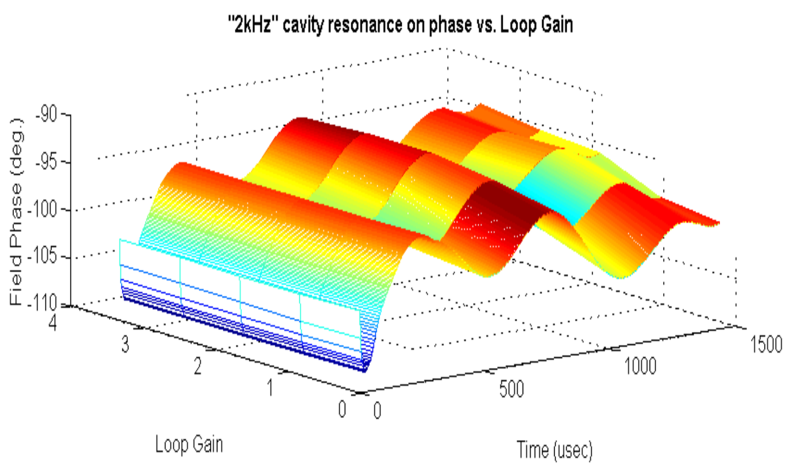


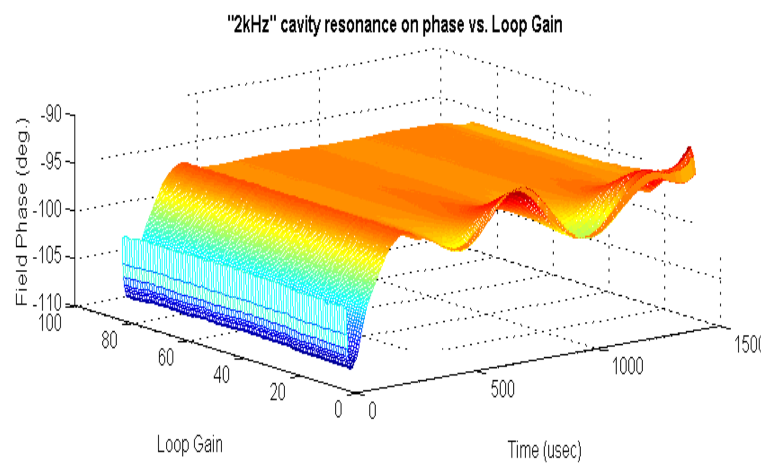
Example 3:

Scanning loop gain to observe the coupling of “2kHz” mechanical mode between field phase and amplitude in association with gain value.





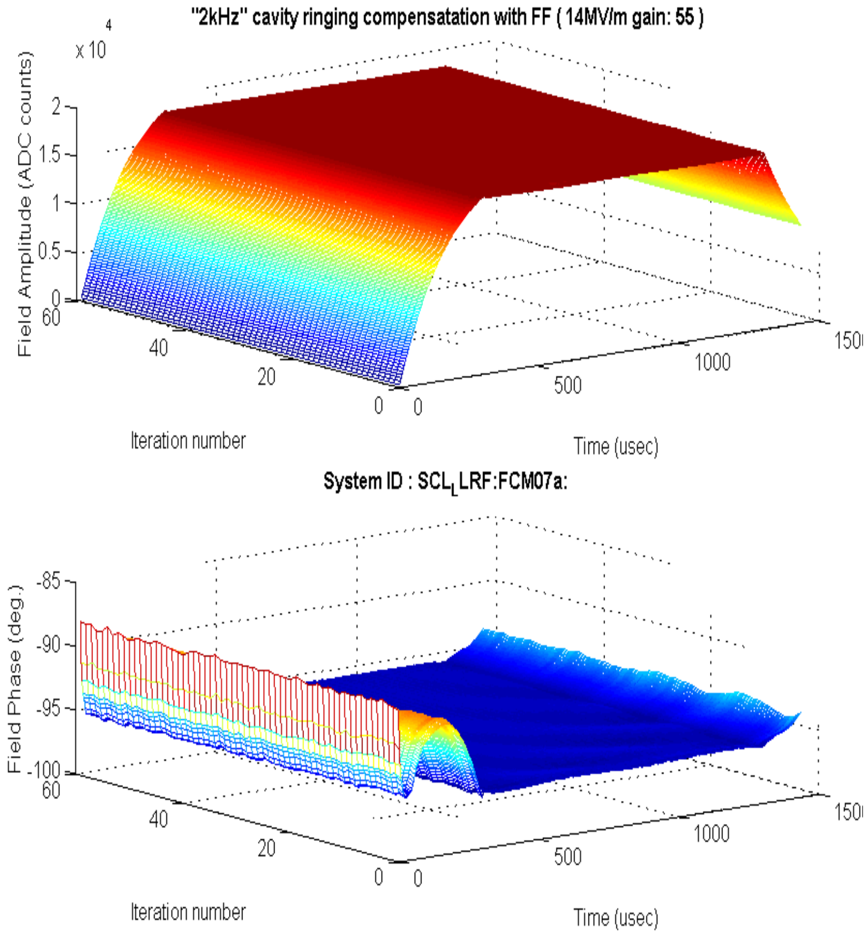


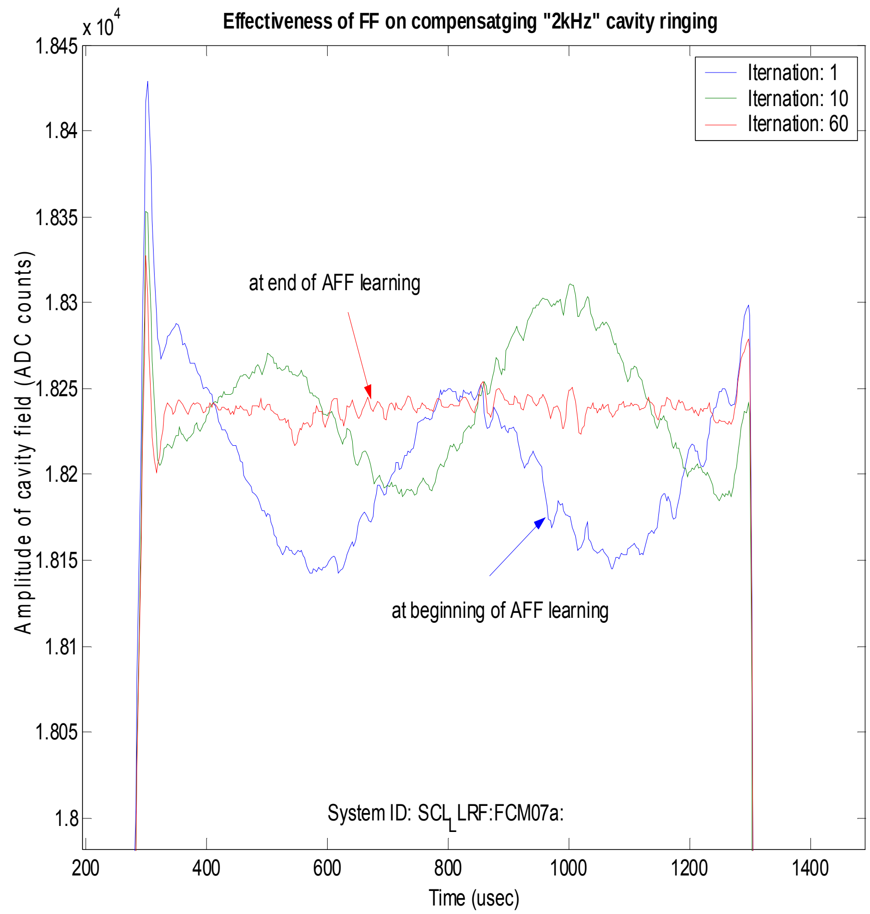


SNS LLRF : DSO buffer feature applications

Example 4:

Observing effectiveness of FF for suppressing the “2kHz” mechanical mode.

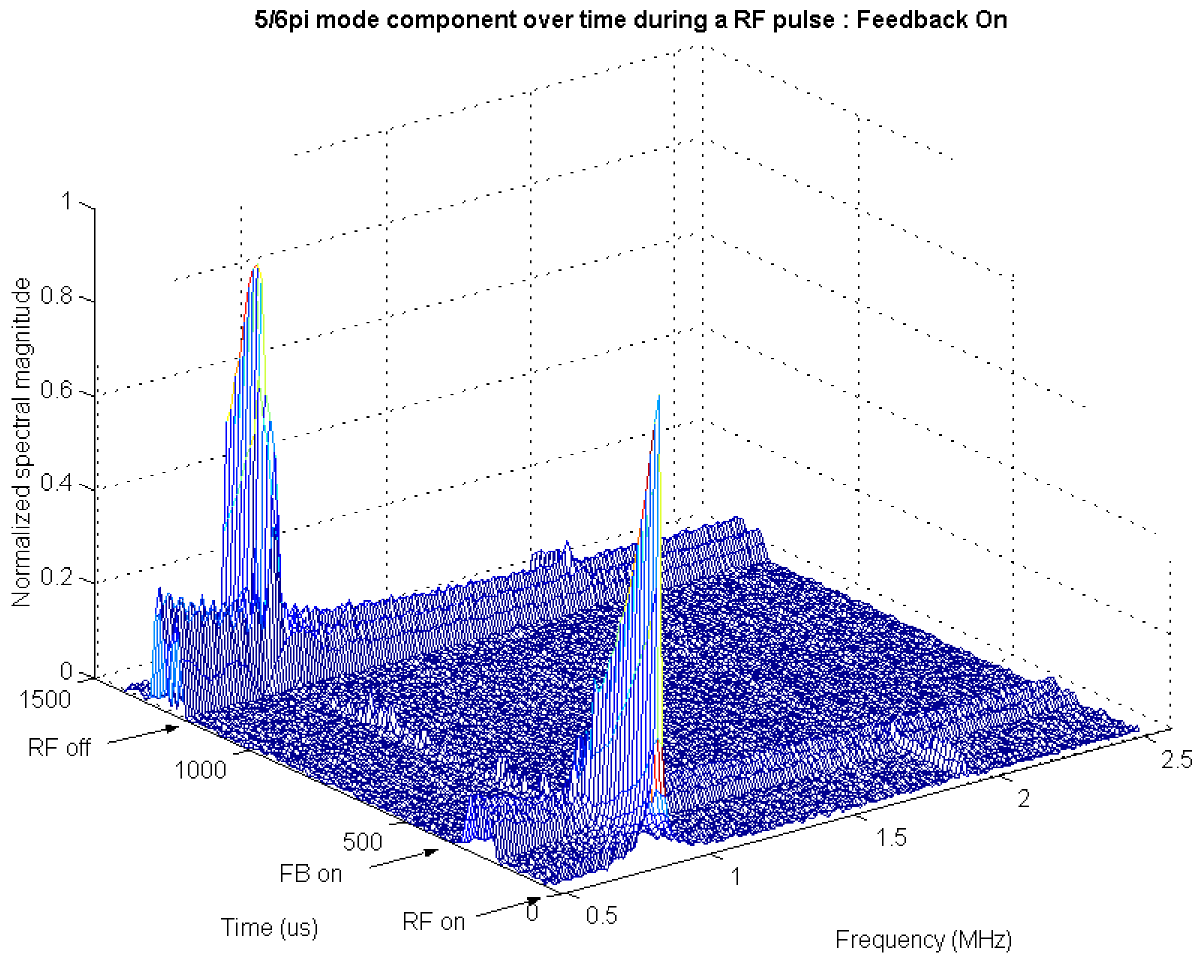




SNS LLRF : DSO buffer feature applications

Example 5:

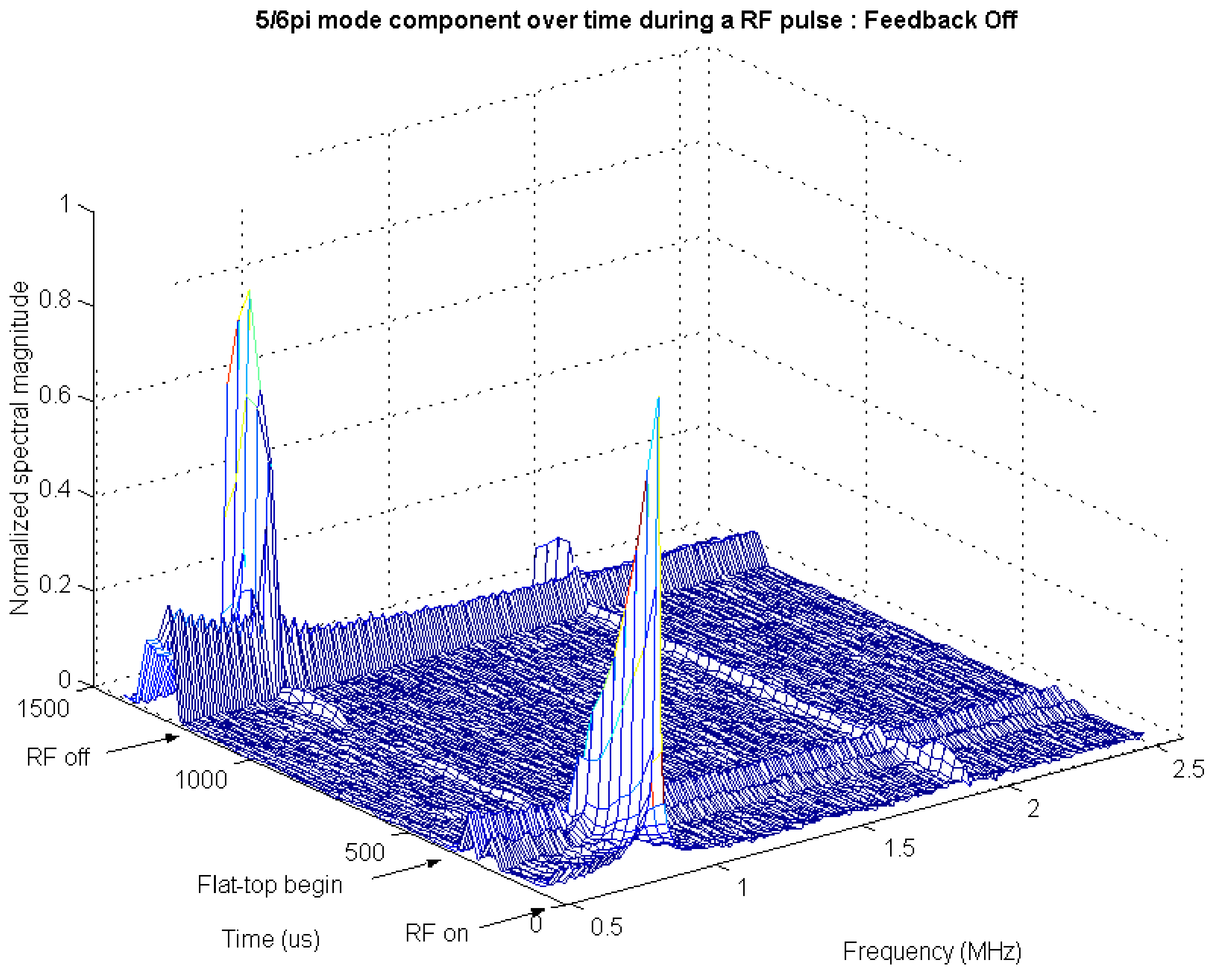
Observing 5/6pi mode over time in closed-loop control mode.



- Insignificant amount of 5/6 pi mode observed at RF turn-on and off
- 5/6 pi mode decays rapidly and is further significantly reduced during flat-top when feedback is turn on.
- Moving window =25us,
- Sampling rate = 5MHz.

Example 6:

Observing the 5/6pi mode over time in open-loop mode.



- 5/6 pi mode is also greatly reduced at and during the flat-top time EVEN WHEN FB IS OFF.
- Cancellation effect from FF pattern ?

Summary

- System performed well and met the needs during the commissioning runs.
- Hardware platform has flexibility and capacity to allow further expansions.
- Strong software support has offered ease and convenience of operations.
- Efforts will continue to focus on algorithms for various AFF compensations, as well as issues in Lorentz detuning.
- Exercises of new hardware and control algorithms for future LLRF.

Acknowledgment

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